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# Airborne Sensor Survey for the Detection of Hazardous Substances and Objects in the Subsurface.

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## 1 Introduction

In recent years there has been a surge of interest in methods for a rapid and reliable detection of unexploded ordnance (UXO) and other hazardous substances and objects in the subsurface. In Germany much of the motivation comes from recent environmental protection projects for the investigation and clean up of former military and industrial sites. The tremendous size of these areas to be investigated made it necessary to find innovative methods to get a rapid view of the contaminations for upcoming planning tasks and also to minimize the costs for necessary ground based surveys and clean up.

Having been the prime contractor for a large project for the investigation of the contamination of more than 1000 former military sites of the West Group of the Russian Troops (WGT) in Eastern Germany the IABG gained an valuable amount of information and knowledge about the problems of the clean up of hazardous waste on military sites. As a result IABG started a research and development project using airborne sensor systems for the survey and detection of hazardous substances and UXO in 1997. This project is partially funded by the Federal Ministry of Education and Research. Parallel to IABG´s R&D project and in close cooperation with IABG another federal institution did similar reasearch but with other airborne sensor systems. Both R&D projects will end in spring 1999 with final reports due in mid 1999. After publication by the German Environmental Agency (UBA) the reports will be available for the public.

## 2 Scope of Work

The main goals of the R&D projects are the investigation of
- the usefulness of various airborne sensor systems
- the improvement of used systems and software
- the determination of the limits of the used systems

for the detection and assessment of various types of hazardous waste and UXO. The detection of unexploded ordnance was not the main goal, but at least with the system used by IABG this investigation was a important aspect.

In the R&D project several survey techniques were used, among them
- aerial imagery,
- magnetic and electromagnetic geophysical sensors,
- multispectral (MSS) and thermal scanner.

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All systems were installed in or at the bottom of a helicopter including ancillary equipment such as real time differential corrected Global Positioning System (GPS) navigation and data positioning, laser and radar altimeter.

## 3 The WGT Project

In the „Treaty between the Federal Republic of Germany and the Union of Soviet Socalist Republics on the Conditions of Limited Residence and the Modalities of the Scheduled Withdrawal of the West Group Troops (WGT) from the Territory of the federal Republic of Germany" as well as in joint declaration of Chancellor Helmut Kohl and President Boris Yeltsin in Moscow on 16th December 1992, the withdrawl of the former Soviet troops was settled for the period between 1991 and 31th August 1994. More than 1000 real estate properties with a total size of approx. 243.000 hectars (ha) were returned, divided up into different sized lots (from 100 sqm to 25.666 ha), being of different structures and of various types of utilisation. At the beginning of 1991 the former Federal Ministry of the Environment. Nature Conservation, and Nuclear Safety in agreement with the federal Ministry of Finance commissioned the determination and evaluation of the residual load sites on all above mentioned real estate properties of the WGT. This project was being carried out under the leadership of IABG together with 30 partner companies located in the new federal states. Of the properties investigated, 529 had already been used as military bases before 1945. More than 33.000 residual load sites were registered. The suspected residual load sites recorded can be divided into the following main groups according to the waste and contamination found:

- operational substances (fuels and lubricants)
- ammunition and explosives
- burials of waste and earth movements
- scrapyards
- residue of burning processes
- indiscriminate dumpings
- waste water and sewage sludge
- miscellaneous

The estimated quantity of all contaminants on the WGT properties were about 2.95 million tons with approx. 1.3 million tons mineral waste, 750.000 tons metal scrap, 456.000 tons residental waste, 126.000 tons of mineral oil products, 100.000 tons organic waste, 83.000 tons of earth movements, 20.000 tons of explosives and ammunition, 8.180 tons of organic chemicals.

Another result of the investigation of the WGT sites was, that there are areas not only with contamination on the surface but also in the subsurface. In addition often times a detailed groundbased survey was either not possible without endangering the survey team or the size of the area would cause an explosion of the costs for a ground based survey.
In 1992 IABG presented a detailed concept as well as practical demonstration of ground based and airborne sensors for the survey of residual load sites within the WGT project. However, the detection of hazardous waste objects and UXO in the subsurface was not part of the WGT project.

## 4 Aerogeophysical Research & Development Project

In a R&D project started in 1996/97 IABG and BGR did the above mentioned aerogeophysical survey with different sensor systems on two areas (TÜP Jüterbog / Heidehof, TÜP Lieberose), all situated on former Russian military sites in eastern Germany. Among the areas flown were

- a tank bunker,
- military garbage dumps / scrapyards,
- two training areas for chemical warfare and

- two test sites prepared by IABG with various types of ordnance, debris and underground pipeline (2500 kg to 2 kg) typical of active sites.

The test site in Jueterbog/Heidehof was made up of 13 areas each 50m x 50m of size. The single areas contained e.g.
- 12 steel barrels (each 120 litre volume)
- 6 barrels
- 4 barrels
- 2 barrels
- 1 barrel
- metal scrap
- various ammunition
- 1 metal tank (1.2m diameter, 2.4 m long)

Airborne survey was done in the summer of 1997 and 1998. In the time between the flights the measurements were evaluated and interpreted thus providing necessary information for the further development and optimization of the sensor systems and the used algorithms and software for the data processing.

In the R&D projects described here, the following airborne methods were used:
- measurements of the earth´s magnetic field
- electromagnetic induction (EM)
- multispectral scanner

Before the airborne measurements a geodetic survey was done for the areas to be surveyed including the set up of identification marks. After each survey airborne imagery was taken. In addition aerial imagery from the WGT project was available for most areas.

After the data processing and interpretation a ground based survey has to be done for the verification of some areas. This verification will be finished by the end of April 1999.

## 5 Ground Based Survey Methods

The common investigation of contaminated sites is done on the ground. For large areas products from a remote sensing survey, such as aerial imagery, in combination with a geodetic survey using GPS ore differential GPS are used for the registration of the geographic position of contaminated points or areas. In addition, ground based survey may be necessary (if possible) for the verification of an airborne survey. The methods of ground based survey are well known. For the detection of hazardous objects and UXO in the subsurface geophysical prospecting methods are mainly used. Among these methods are:
- Electromagnetic induction measurements (EMI, EM), taking advantage of the different conductivity of layers in the subsurface
- Electromagnetic reflectance (EMR, Geo-Radar)
- Measurements of the earth´s magnetic field or of its gradients using portable magnetometers

## 6 Remote Sensing Survey Methods

Besides ground based methods for the investigation of contaminated sites airborne or satellite based methods provide information about contamination on and below the surface. With various sensors measurements and images can be taken in various frequencies of the electromagnetic spectrum. Among these methods are:

- Satellite imagery (black/white (b/w), color, multispectral, radar)
- Airborne imagery (b/w, color, color infrared (CIR), radar)

- Airborne geophysical survey (EM, Magnetic field measurements)
- Multi- and Hyperspectral Scanner Imagery ( from about 380 nm to 2450 nm)
- Thermal and Thermal Infrared Imagery (800 nm to 14000 nm)
- Laserspectroscopic measurements
- Gammaspectroscopic measurements
- Stereoscopic Imagery and Laser Scan measurements (for Digital Elevation Models)

Some methods will provide indirect information about contamination or are necessary for optimizing the interpretation of data using another method. Hyperspectral scanners can deliver data in up to 128 multispectral bands with a spectral resolution of 12 - 16 nm and a spatial resolution below 3 metres gained at flight height of 1250 metres. High resolution stereo scanners gather multispectral data plus stereo imagery with a spatial resolution of 15cm to 20cm at flight heights of 400 metres. This enables the calculation of high resolution Digital Elevation Models (DEM) with pixels sizes of 0.5 metres or less. Multispectral imagery can give important information about contamination on the earth´s surface. This may also be an indication of contamination in the subsurface.

## 7 Geophysical Methods

It is fairly easy to find buried hazardous substances or UXO using ground based metal detectors as long as the objects looked for contain a certain degree of metal. An important problem in ground based range remediation today is discriminating between buried UXO and clutter or other hazardous waste. The sensors which reliably detect subsurface objects with metal components are magnetometers and electromagnetic induction (EMI).
For very large areas, such as shooting grounds or training areas a ground based survey is a very expensive and time consuming action.

The legitimacy for an airborne instead of an ground based survey usually is:
- having a large or very large are to investigate
- having complicated topopgraphy of the area
- neccessity to get a quick overview of the geological layers
- ground based survey is not possible without danger for the survey team
- to get a quick and cost effective overview of the contamination
- to detect the main areas with accumulations of hazardous waste and UXO to optimize / minimize ground based survey

Thus, results from an airborne survey should help to optimize the planning of ground based surveys and clean up activities thus minimizing the costs for these tasks.

### *7.1 Helicopter based electromagnetic survey*

The electromagnetic methods (EM) measure the changes and anomalies of the electromagnetic fields caused by differences and changes in the conductivity of the subsurface. The EM will register very well the lateral variations of the geology. This method is mainly used for hydrological tasks and groundwater mapping. The depth penetration is 50 metres and more. Within the EM active and passive methods are used. The passive method uses signals transmitted from a radio station or from a submarine transmitter (producer of the primary electromagnetic field). The active method has transmitter and receiver combined in the sensor system. The primary field induces electric currents in the conductive zones and layers in the earth thus generating a secondary field, which will be converted within the sensors receiver into an electric signal and registered. The aim is the determination of the distribution of the electric conductivity in the subsurface. The reciprocal is the specific (electric) resistance. If groundwater is contaminated the specific resistance will show lower values than in groundwater not being contaminated.

In the mentioned R&D project BGR concentrated on using and optimizing their EM system. This system together with a single magnetometer is installed in a cigar-type container hanging on a cable about 20m - 30m below the helicopter.

A new construction of an multifrequency EM-system with five frequencies was used:

- 375 Hz
- 1972 Hz
- 8600 Hz
- 41000 Hz
- 195000 Hz

The newly added high frequency enables a better resolution of the region close to the surface.

A detraction of EM-measurements can always occur due to

- instabilities in the compensation of the primary field, e.g. through forces upon the sensor system by temperature etc.
- changes in the external magnetic field (power lines, solar flares)
- bad quality of the calibration (calibration done on high conductive subsoil)
- unprecise split of the measured secondary field into „inphase - and quadrature"-components

In addition to the EM-signals further parameters were recorded

- atmospheric disturbances (spherics)
- position of the helicopter and the sensor system (GPS)
- flight altitude (radar)
- barometric altitude
- time intervals (fiducials)

In the project the interpretation of the measurements could be optimized due to

- using five instead of three frequencies in the EM system
- using a higher scan rate (10 per sec instead of 4 per sec)
- a new calibration concept for the sensor system
- a better noise-to-signal ratio of the new system
- a stable compensation of the primary field
- using newly optimized algorithms
- using a new GPS system in the helicopter

The use of five frequencies instead of three caused better results in the computer aided modelling.

For an overview of the hydro- and geological situation on both areas (approx. 200 sqkm) EM-sensorflight were done with a line spacing of 150m or 200m. The mean height of the sensor was 25m above ground. The test site in Jueterbog/Heidhof and some larger areas (approx. 86 sqkm) were surveyed with a line spacing of 50 m.

### *7.2 Helicopter Based Magnetic Survey*

Magnetometers are being used to measure the total field intensity of the earth magnetic field and, if used in a combination of several magnetometers, the change of the field, the vertical or horizontal magnetic gradient. The vertical component of the spatial gradient, or simply the gradient, is obtained by differencing two simultaneous measurements of the magnetic induction and dividing it by the sensor separation. For example, the geomagnetic field has an average magnitude at the earth´s surface of about 40.000 nT to 60.000 nT ( 1 gamma = $10^{-5}$

= $10^{-5}$ oersted = $10^{-9}$ webers/$M^2$ = $10^{-9}$ tesla = 1 nano tesla or nT ). All field strength values are reported in nT, all spatial gradients of the field are reported in nT/m.
There are regional variations of the geomagnetic field plus time variations with periods of seconds, minutes and hours as direct or indirect effects of the solar wind distorting the magnetosphere or external magnetic field. Daily or diurnal variations are not predictable and may exhibit changes ranging from 10nT to 1000 nT or more. Therefore a ground based magnetometer is used to measure the local diurnal changes during a campaign. Magnetic anomalies in the earth magnetic field are caused by two different kinds of magnetism: induced and remanent (permanent) magnetization. The remanent or permanent magnetization is often the predominant magnetization (relative to the induced magnetization) in many igneous rocks and iron alloys. It depends upon the thermal, mechanical and magnetic history of the specimen, and is independent of the field in which measured. Induced magnetization refers to the action of the field on the material wherein the ambient field is enhanced and the material itself acts as a magnet (such as UXOs, steel barrels, tanks, etc.).

Aeromagnetic surveys were conducted by IABG on several areas on the Jueterbog and Lieberose sites in 1997 and 1998 for a total of about 2 - 3 weeks in each year.
Survey areas for this campaign were the same as mentioned above for the EM survey. In addition a second test site with 10 areas, 50m x 40m each, was built up in Lieberose in summer 1998. This test site contained

- 3 barrels
- 2 barrels
- 2 x 1 barrel
- metal scrap
- UXO-like iron with masses ranging from 35kg to 1.9 kg

Metal content of 35kg and 11kg represent the metal content of the majority of the shells (granades) found on the WGT site. The orientation of all objects within the earth´s magnetic field was changed for each flight thus having measurements for most of the possible positions of the objects.

For the 1997 survey IABG used two magnetic sensor systems. The so-called X-wing system and the HM3-system. In 1998 only the HM3 was used for survey at the Lieberose site.

**The X-wing system** is a 3-gradiometer sensor system with four Geometrics cesium magnetometers each separated by a distance of 1.5 metres in a configuration like an X. The sensors are built in a container similar to the EM-system being towed 30 meters below the helicopter. The X-wing system will measure the total field strength and the total gradient (analytic signal) of the local geomagnetic field.

**The HM3** system is a newly developed sensor system (Helicopter Mounted Magnetic Mapping System) first used in 1997. This system is using 3 Geometrics cesium magnetometers each placed at one end of three (6 m long) plastic tubes. All tubes are fixed to the bottom of the helicopter, one at starboard, one at port and one showing out at the front of the helicopter. This way you have 3 magnetometers each six meters apart.
The following parameters were measured:

- total magnetic field
- local magnetic anomalies
- diurnal magnetic variation
- other influencing fields (helicopter)
- flight altitude (laser & radar altimeter)
- position of the helicopter using differential GPS

A ground based GPS station was placed on geodetic surveyed positions to enable dGPS measurements.
The scan rate of the HM3 is 1000 Hz. In further steps of the data processing the data were scanned in 20 Hz. This is necessary to reduce noise signals generated from the helicopter and from the earth´s atmosphere by destructive interference. The IABG owned Bell LongRanger 206 had been thoroughly tested and measured in IABG´s large Magnetic Field Simulation Facility (MFSA) normally used for checking satellite systems before launching them into space.
The raw data gathered with the HM3 contain 9 different signals measured. The necessary correction using the measurements of the diurnal variation, sensor and helicopter altitude and position and other parameters is done with an optimized standard software package OASIS *montaij* from GeoSoft. This package contains a separate software module for UXO target analysis from magnetic data.

## 8 Results

With the X-Wing as well as with the HM3 system all objects in the test site at Jueterbog / Heidehof including the pipeline were detected during the 1997 survey. To find out the limits for the detection of subsurface objects the HM3 system was used in 1998 and the second test site in Lieberose was filled with object much smaller in size and weight than for the 1997 test site in Jueterbog / Heidehof.

Thanks to the new and unique helicopter mounted magnetic mapping system the navigation, maneuverabilty and flight height of the helicopter and the sensor system could be optimized compared to using the X-wing system. With the HM3 system survey lines were interleaved so that the three traces of the magnetic data collection for each flight line provided a nominal spacing of 3 metres with flight heights ranging from 15 m down to 2.5 metres. These parameters were certainly a main factor in gaining usable signals from all objects, even from smaller objects, e.g. a 5.3 kg iron, that could not be detected by airborne surveys in the past.

The EM system used by BGR detected many of the objects buried in the Jueterbog/Heidehof test site. Despite a sensor height of 25m above ground improved postprocessing and filtering algorithms made it possible to definitely improve the evaluation and interpretation of the EM and magnetic signals measured.

In addition the combination (overlay) of recent and historical aerial imagery, thermal, MSS (multispectral scanner) and magnetic data within a geographic information system (GIS) leads to a more reliable and precise interpretation of the measurements.

The final interpretation of the data taking in consideration the still to be processed ground based verification data as well as the final report will be finished in June 1999.

Compared to former airborne surveys using EM or magnetometers sensors the results gained so far during this R&D project with the improved or new systems and methods already show quite some remarkable improvements for the detection of hazardous substances and objects (like UXO) in the subsurface.